# ELECTROMAGNETIC METHOD AND APPARATUS FOR DETERMINING THE NATURE OF SUBTERRANEAN RESERVOIRS USING REFRACTED ELECTROMAGNETIC WAVES

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## Related Application

This application is a continuation of Application No. 10/214,471 filed August 7, 2002, which claims priority to GB 0119245.9, filed August 7, 2001, which is incorporated herein

10    by reference.

## Technical Field

The present invention relates to a method and apparatus for determining the nature of submarine and subterranean reservoirs. The invention is particularly suitable for

15    determining whether a reservoir, whose approximate geometry and location are known, contains hydrocarbons or water, and also for detecting reservoirs with particular characteristics.

## Background of the Invention

Currently, the most widely used techniques for geological surveying, particularly

20    in sub-marine situations, are seismic methods. These seismic techniques are capable of revealing the structure of the subterranean strata with some accuracy. However, whereas a seismic survey can reveal the location and shape of a potential reservoir, it can normally not reveal the nature of the reservoir.

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## Summary of the Invention

The solution therefore is to drill a borehole into the reservoir. However, the costs involved in drilling an exploration well tend to be in the region of £25m and since the success rate is generally about 1 in 10, this tends to be a very costly exercise.

5      It is therefore an object of the invention to provide a system for locating a subterranean reservoir and for determining, its nature with greater certainty, without the need to sink a borehole.

It has been appreciated by the present applicants that while the seismic properties of hydrocarbon filled strata and water-filled strata do not differ significantly, their

10     electromagnetic resistivities do differ. Thus, by using an electromagnetic surveying method, these differences can be exploited and the success rate in predicting the nature of a reservoir can be increased significantly. This represents potentially an enormous cost saving.

Consequently, a method and apparatus embodying these principles from the basis of the present applicant's co-pending British patent application No. 0002422.4, and co-pending.

15     U.S. application No. 10/123,867, incorporated herein by reference.

This contemplates a method of determining the nature of a subterranean reservoir whose approximate geometry and location are known, which comprises: applying a time varying electromagnetic field to the strata containing the reservoir; detecting the electromagnetic wave field response; seeking in the wave field response, a component representing a refracted wave

20     from the hydrocarbon layer; and determining the content of the reservoir, based on the presence or absence of a wave component refracted by the hydrocarbon layer.

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It also contemplates a method for searching for a hydrocarbon containing subterranean reservoir which comprises: applying a time varying electromagnetic field to subterranean strata; detecting the electromagnetic wave field response; seeking, in the wave field response, a component representing a refracted wave; and determining the presence and/or

5    nature of any reservoir identified based on the presence or absence of a wave component refracted by hydrocarbon layer.

It further contemplates an apparatus for determining the nature of a subterranean reservoir whose approximate geometry and location are known, or for searching for a hydrocarbon containing subterranean reservoir, the apparatus comprising: means for applying a

10    time varying electromagnetic field to the strata containing the reservoir; means for detecting the electromagnetic wave field response; and means for seeking, in the wave field response, a component representing a refracted wave, thereby enabling the presence and/or nature of a reservoir to be determined.

A refracted wave behaves differently, depending on the nature of the stratum in

15    which it is propagated. In particular, the propagation losses in hydrocarbon stratum are much lower than in a water-bearing stratum while the speed of propagation is much higher. Thus, when an oil-bearing reservoir is present, and an EM field is applied, a strong and rapidly propagated refracted wave can be detected. This may therefore indicate the presence of the reservoir or its nature if its presence is already known.

20    Electromagnetic surveying techniques in themselves are known. However, they are not widely used in practice. In general, the reservoirs of interest are about 1 km or more below the seabed. In order to carry out electromagnetic surveying as a stand alone technique in

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these conditions, with any reasonable degree of resolution, short wavelengths are necessary. Unfortunately, such short wavelengths suffer from very high attenuation. Long wavelengths do not provide adequate resolution. For these reasons, seismic techniques are preferred.

5    However, while longer wavelengths applied by electromagnetic techniques cannot provide sufficient information to provide an accurate indication of the boundaries of the various strata, if the geological structure is already known, they can be used to determine the nature of a particular identified formation, if the possibilities for the nature of that formation have significantly differing electromagnetic characteristics. The resolution is not particularly important and so longer wavelengths which do not suffer from excessive attenuation can be

10   employed.

The resistivity of seawater is about 0.3 ohm-m and that of the overburden beneath the seabed would typically be from 0.3 to 4 ohm-m, for example about 2 ohm-m. However, the resistivity of a hydrocarbon reservoir is likely to be about 20-300 ohm-m. Typically, therefore, the resistivity of a hydrocarbon-bearing formation will be 20 to 300 times greater than that of a

15   water-bearing formation. This large difference can be exploited using the techniques of the present invention.

The electrical resistivity of a hydrocarbon reservoir normally is far higher than the surrounding material (overburden). EM-waves attenuate more rapidly, and travel slower inside a low resistivity medium, compared to a high resistivity medium. Consequently, hydrocarbon

20   reservoir will attenuate EM-waves less, compared to a lower resistivity overburden. Furthermore, the EM-wave speed will be higher inside the reservoir.

Thus, an electric dipole transmitter antenna on or close to the sea floor induces electromagnetic EM fields and currents in the sea water and in the subsurface strata. In the sea water, the EM-fields are strongly attenuated due to the high conductivity in the saline environment, whereas the subsurface strata with less conductivity causes less attenuation. If the

5      frequency is low enough (in the order of 1 Hz), the EM energy is able to penetrate deep into the subsurface, and deeply buried geological layers having higher electrical resistivity than the overburden (as e.g. a hydrocarbon filled reservoir) will affect the EM-waves. Depending on the angle of incidence and state of polarisation, an EM wave incident upon a high resistive layer may excite a ducted (guided) wave mode in the layer. The ducted mode is propagated laterally along

10     the layer and leaks energy back to the overburden and receivers positioned on the sea floor. In the present application, such a wave mode is referred to as a "refracted wave".

The distance between the EM source and a receiver is referred to as the offset. Due to the fact that a refracted wave in a hydrocarbon-bearing formation will be less attenuated than a direct wave in seawater (or in the overburden), for any given H/C bearing formation, there

15     will be a critical offset at which the refracted wave and the direct wave will have the same signal strength. This may typically be about two to three times greater than the shortest distance from the source (or receiver) to the H/C bearing formation. Thus, when the offset is greater than the critical offset, the radial EM waves that are refracted into, and guided through the reservoir, will pay a major contribution to the received signal. The receiver signal will be of greater magnitude

20     and arrive earlier (i.e. have smaller phase) compared to the case where there is no HC reservoir. In many cases, the phase change and/or magnitude change recorded at distances greater than the

critical offset, may be directly used for calculation of the reservoir resistivity. Furthermore, the reservoir depth may be inferred from the critical offset and/or the phase and magnitude slopes for various source – receiver offsets.

The present invention has arisen from this realisation.

5    According to one aspect of the present invention, there is provided, a method of investigating subterranean strata which comprises: deploying an electric dipole transmitter antenna; deploying an electric dipole receiver antenna at a predetermined offset distance from the transmitter; applying an electromagnetic (EM) field to the strata using the transmitter; detecting the EM wave field response using the receiver, extracting phase information from the

10   wave response; repeating the procedure with the transmitter and/or receiver in different locations for a plurality of transmissions; and using the phase information from the wave response for the plurality of transmissions, in order to determine the presence and/or nature of the reservoir.

Thus, the offset can be varied by moving the receiver; or indeed the transmitter, or even both. Alternatively, the predetermined offset can be kept constant by moving both the

15   transmitter and receiver.

Thus, the horizontal boundaries of the reservoir may be found by analysing the slope and/or slope change of the curve(s) of phase and/or magnitude as a function of source-receiver offset distance or position, or by analysing the variation in phase and/or magnitude for a

fixed source-receiver offset at several locations. The most useful source-receiver offset is typically larger than the "critical offset". In this part of the curve, the change in slope, may indicate the reservoir boundary.

Both the source and the receiver are preferably inside the reservoir area to achieve

5 the smallest slope (or gradient). This is true for both the phase and the magnitude curves. Soon after either the source or the receiver leaves the reservoir area, the slopes increases rapidly. From the position where this change occurs, the reservoir boundary may be mapped. The true reservoir boundary will probably lie closer the centre of the reservoir compared to the location where the slope change occurred, typically 10 to 20% of the reservoir depth. The detailed

10 position may be calculated using the measured data and forward modelling.

This technique of the invention can be used in conjunction with conventional seismic techniques to identify hydrocarbon reservoirs.

If the offset between the transmitter and receiver is significantly greater than three times the depth of the reservoir from the seabed (i.e. the thickness of the overburden), it will be

15 appreciated that the attenuation of the refracted wave will often be less than that of direct wave and the reflected wave. The reason for this is the fact that the path of the refracted wave will be effectively distance from the transmitter down to the reservoir i.e. the thickness of the overburden, plus the offset along the reservoir, plus the distance from the reservoir up to the receivers i.e. once again the thickness of the overburden.

20 If no H/C reservoir is present in the area of the transmitter and receiver, the phase of the detected wave response will consist of a direct wave and will therefore change linearly

with a changing offset. Similarly, the phase of the detected wave response will remain constant at a constant offset in different locations.

However, if an H/C reservoir is present, there will be a refracted wave component in the wave response and this may predominate. Due to the higher phase velocity (wavespeed)

5 in H/C filled strata, this will have an effect on the phase of the received wave response. In the case of an increasing offset, the phase will not change linearly; a plot of phase against offset will be a curve with a constantly changing slope. Thus, a change from a straight line to a curve, or vice versa, will indicate the boundary of an H/C reservoir.

In the case of a constant offset, the presence of an H/C reservoir will give rise to a

10 constant but different phase value at different locations compared to the situation where no H/C reservoir is present. Thus, a change in phase value will indicate the boundary of an H/C reservoir.

Preferably, the procedure is repeated at different offsets.

In one embodiment, the method includes plotting a graph of the phase of the

15 refracted wave response from a particular stratum against offset and analysing the slope of the graph in order to determine the nature of the stratum. Alternatively, the method includes plotting a graph of the phase of the reflected wave response from a particular stratum and identifying a change in the slope of the graph.

In another embodiment, the method comprises repeating the procedure at different

20 locations, using the same predetermined offset, and analysing the phase of the refracted wave response from a particular stratum in order to identify a change in the phase value.

The polarization of the source transmission will determine how much energy is transmitted into the oil-bearing layer in the direction of the receiver. A dipole antenna is therefore the selected transmitter. In general, it is preferable to adopt a dipole with a large effective length. The transmitter dipole may therefore be 100 to 1000 meters in length and may

5      be towed in two orthogonal directions. The receiver dipole optimum length is determined by the thickness of the overburden.

The technique can be applicable in exploring land-based subterranean reservoirs but is especially applicable to submarine, in particular sub-sea, subterranean reservoirs. Preferably the field is applied using one or more transmitters located on the earth's surface, and

10    the detection is carried out by one or more receivers located on the earth's surface. In a preferred application, the transmitter(s) and/or receivers are located on or close to the seabed or the bed of some other area of water.

The transmitted field may be pulsed, however, a coherent continuous wave optionally with stepped frequencies is preferred. It may be transmitted for a significant period of

15    time, during which the transmitter should preferably be stationary (although it could be moving slowly), and the transmission stable. Thus, the field may be transmitted for a period of time from 3 seconds to 60 minutes, preferably from 10 seconds to 5 minutes, for example about 1 minute. The receivers may also be arranged to detect a direct wave as well as the refracted wave from the reservoir, and the analysis may include extracting phase and amplitude data of the refracted wave

20    from corresponding data from the direct wave.

Preferably, the wavelength of the transmission should be in the range

$$0.1s \leq \lambda \leq 5s;$$

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where λ is the wavelength of the transmission through the overburden and s is the distance from the seabed to the reservoir. More preferably λ is from about 0.5s to 2s. The transmission frequency may be from 0.01 Hz to 1 kHz, preferably from 0.1 to 20 Hz, for example 1 Hz.

Preferably, the distance between the transmitter and a receiver should be in the

5    range

$$0.5\,\lambda \le L \le 10\,\lambda;$$

where λ is the wavelength of the transmission through the overburden and L is the distance between the transmitter and the first receiver.

It will be appreciated that the present invention may be used to determine the

10   position, the extent, the nature and the volume of a particular stratum, and may also be used to detect changes in these parameters over a period of time.

The present invention also extends to a method of surveying subterranean measures which comprises; performing a seismic survey to determine the geological structure of a region; and where that survey reveals the presence of a subterranean reservoir, subsequently

15   performing a method as described above.

The invention may be carried into practice in various ways and will now be illustrated in the following simulated Examples.

Brief Description of the Drawings

20   Figure 1 is a schematic representation of a situation in which measurements are taken outside the area of a reservoir;

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Figure 2 is a schematic representation of a situation in which measurements are taken inside the area of a HC reservoir;

Figure 3 is a schematic representation of a situation in which measurements are taken crossing a H/C reservoir boundary;

5    Figure 4 is a view similar to Figure 3, in which the receiver is in a borehole; and

Figure 5 is a graphical representation of the results from the situations in Figures 1 to 4.

## Detailed Description of the Drawings

10    In Figures 1 to 4, it is assumed that the sea 11 has a resistivity of 0.3 ohm-m and a depth of 1000m from the surface 12 to the seabed 13. The overburden 14 has a resistivity of 0.7 ohm-m. The transmitted wave had a frequency of 1 Hz.

Figure 1 shows the situation where a receiver 15 and a transmitter 16 are located on the seabed 13 in a region where there is no subterranean reservoir. The position of the

15    receiver 15 is fixed. The transmitter 16 is moved to various different positions resulting in different offsets from the receiver 15. At each position of the transmitter 16, an EM field is transmitted and the wave field response is detected by the receiver 15. The wave field response includes a direct wave component and reflected wave components. Phase information is extracted for each response and the results are plotted as a graph in Figure 5. The plot of phase

20    against offset (source-receiver distance) is a straight line 51, showing that the phase varies linearly with offset.

Figure 2 shows the situation where the transmitter 15 and receiver 16 are deployed in a region where there is a subterranean H/C reservoir 17. The reservoir 17 is 100m thick and has a resistivity of 50 ohm-m, and is located at a depth of 800 m beneath the seabed 13. The procedure described in relation to Figure 1 is repeated and again the results are shown in

5      Figure 5.

In this case, the wave field response additionally includes a refracted wave component from the reservoir 17. This affects the phase of the response and results in the plot of phase against offset taking the form of a smooth curve 52, with a constant change of slope.

Figure 3 shows the situation where the transmitter 15 and receiver 16 are

10     deployed in a region where there is an H/C reservoir 18 with a boundary 19. The reservoir 18 is similar to that in Figure 2 but its boundary 19 is at a position 3km away from the position of the transmitter 15. Again, the procedure described in relation to Figure 1 is repeated and the results are shown in Figure 5.

In this case, the wave field response phase curve 53 initially follows the curve 52

15     of the results from Figure 2 but soon after an offset of 3km, the results follow a straight line which has the same slope as the line 51 of the Figure 1 situation. The change in slope of the curve 52 clearly shows the presence of a boundary between an H/C reservoir and no H/C reservoir. The position of the boundary 19 can be deduced from the position of the change in slope.

20     The situation shown in Figure 4 is similar to that of Figure 3 except that in this case, the receiver 25 is located in a well bore 27 and the transmitter 26 is moved to different

locations to vary the offset. Once again, the procedure described in relation to Figure 1 was repeated and the results are shown in Figure 5.

Due to the location of the receiver 25 in a well bore 27 and within the reservoir 18, the phase curve 54, as the offset increases, follows a straight line initially. The slope of the

5      initial portion is shallower than the slope of the curve 51 where no H/C reservoir was present, due to the effect of the presence of a direct wave propagated through the H/C reservoir. However, soon after an offset of 3km, the slope of the curve 54 begins to change and continues to change until it attains the same slope as the curve 51 of Figure 1. This change again shows clearly the presence of an H/C reservoir boundary and its position can be deduced from the

10     position of the change in the slope of the curve 54.